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APPLYING THE RESULTS OF EXPERIMENTS ON SMALL MODELS
IN THE WIND TUNNEL TO THE CALCULATION OF FULL-SIZED AIRCRAFT

Par le Chef d'Escadron d'Artillerie Robert, S.T.Aé.

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APPLYING THE RESULTS OF EXPERIMENTS ON SMALL MODELS IN THE WIND TUNNEL TO THE CALCULATION OF FULL-SIZED AIRCRAFT.*

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Use of results obtained in the wind tunnel may be made in two ways: the different parts of the airplane, such as wings, fuselage, struts, etc., may be tested separately on small scale and may be calculated in full size by applying the laws of similitude by which we can know the proper coefficients for the full-sized parts. We may also test in the wind tunnel a complete model of the aircraft and attempt to derive from it coefficients which can be applied to the full-sized craft. If it is possible, this method is by far the simpler of the two. In order to examine this question more theoretically it will be useful to make a detailed analysis of the conditions. We must find a law which will permit the use of the results obtained on small models in a tunnel for the calculation of full-sized airplanes, or if it exists, a law of similitude relating the air forces on a full-sized airplane to those on a reduced scale model. This law will apply both to the full-sized airplane and to the model if the two bodies are geometrically similar and move relative to the air under similar conditions.

If we assume the air to be under the same conditions of temperature and pressure, then this law of similitude should express

* Abstract from "Premier Congres International de la Navigation Aérienne", Vol. I, pp 1-13.

the resistance of the large airplane in terms of simple function of the geometrical scale and the respective velocities of the two bodies. For the present, assuming that such a law exists, which is not necessarily certain, let us see if it would apply to the model tests as they are now conducted. We immediately see that it will not, for several conditions differ from those which we have above laid down. These are: first, the model is not geometrically similar to the airplane; second, the airplane moves in a stationary and unlimited fluid while the model is stationary in a moving stream of air limited by walls; third, the airplane is moving freely in the fluid while the model is necessarily held by supports, the presence of which modifies the air flow.

Lack of Geometrical Similitude.

It is impossible to obtain complete similitude for all details and accessories of the airplane. It is obvious that many small parts can not even be approximated in the model and that the effect of these will necessarily modify the results obtained in the laboratory.

Relativity of Motion and the Limited Air Stream.

If the air stream in the tunnel were unlimited or of very great extent in proportion to the model, we could assume the principle of relative motion. Dubat and Duchemin found in experimenting with square plates under water resistance coefficients, which differed, in the ratio of 1.3 to 1. Joukowski explains this by the difference in form of the wake behind the plates; a turbulent flow being behind the stationary plate in the water and a formation of a vortex ring behind the plate which streamlines it in the case of a moving plate in a stationary fluid. This result, called the paradox of Dubat/may be explained by the conditions under which the experiment was made. We now know that at low speeds and for non-streamline bodies the type of flow of the fluid is very unstable and Dubat operated at velocities varying from 2 to 5 meters per second on a thin plate. In the last thirty years, however, many experiments carefully carried out by trained men have been made to determine the specific resistance of an airplane moving perpendicular to itself. Some have been carried out with a moving framework, others with plates falling vertically, and still others by exposing a plate to the pressure of natural or artificial wind. Notable among these are those made between 1908 and 1912 by Mr. Stanton in England, and Mr. Eiffel in Paris, and the results show that for plates of the same dimensions the coefficients are the same for moving or for stationary plates. The fact that the airplane is moving in stationary air while the model is stationary in a stream of air, therefore should not give cause for an appreciable error. The limitation in size of the air stream, however, does introduce a certain error. The S.T.Ae. has carried out a research to determine this error. For this work the two-meter tunnel of the Institute Aerotechnique at Saint-Cyr, consisting of a venturi tube with continuous walls was provided with an experimental chamber of the Eiffel type. This made it possible, while keeping all other conditions consistent, with walls surrounding the air stream. Recent experiments carried out by Mr. Toussaint dealt with three wings of 1-meter span. This span is greater than that of models usually tested. It was used in order to show more clearly the effect of the walls. The presence of the continuous walls increases the lift and decreases the drag of the aerofoil. The decrease in resistance for a given lift is of the same order of magnitude as that predicted from theoretical formulas. These, however, predict that the increase in resistance should be proportional to the square of the lift while the actual experiments show that it increases very much less rapidly. Nevertheless the difference between the polar curve obtained with walls and that obtained with an air stream passing through a large chamber, is sufficiently great to require a correction. If care is taken to use models such that the ratio of the surface to be tested to the cross section of the tunnel is less than 0.7% (Maximum span of 60 centimeters in a two-meter tunnel), the average difference will be of the order of 5 to 6%.

From the data at hand we may conclude that it would be possible, by modifying the theoretical formulas with a suitable coefficient, to calculate the necessary correction to eliminate the effect of limited air stream. Some attention has been given to the effect of turbulence of the air stream and its effect on the measurement of the resistance of spheres. In this work the coefficients found by different investigators are decidedly different and agreement has not been found even for coefficients obtained for the same Reynolds number.

In 1914 Prandtl explained this disagreement by showing that the type of air flow depended on the turbulence of that portion of the fluid which is not immediately in contact with the sphere.

Mr. Toussaint continued this work at the Institute of Saint-Cyr and clearly demonstrated that it is possible to change the regime of high resistance to that of low resistance for very different values of VD by changing the degree of artificial turbulence. These same phenomena have been observed on all types of bodies from which the air stream may be detached or made discontinuous at certain points of the surface. However, this seems to be of very little importance for wings. In any case, it is certain that the degree of turbulence in the air stream depending on the actual construction of the tunnel and particularly on the use and location of diffusers or honeycombs has an influence on the results obtained. This turbulence should be reduced as much as possible.

Interference of the Supports.

The model must necessarily be held by a support, naturally of as small a size as possible and it has been the custom in laboratories to measure the actual resistance of this support and to subtract it from each reading. It was thought that in this manner the influence of the support might be eliminated. It was thought that the interference of the support on the model should be negligible. Experiments on this subject were made this year in the two laboratories of the S.T.Ae., and have shown that the interference of the supports was much greater than it had been supposed, in spite of their small size. These laboratories used a wing of 70-centimeters span and 15 centimeters chord, supported by two small brackets placed one behind the other on the centerline, each made of sheet steel 4 mm thick and 12 mm wide, ending in a square fastening plate 8 mm by 8 mm. The wings were tried with three different methods of holding: First, the brackets above the wing; second, brackets below the wing; and third, a flattened rod attached to the trailing edge. Many tests repeated several times were carried out in the two tunnels with the same models, which included four different wing sections of greatly differing characteristics (Fig. 1). The results of these tests agree absolutely (Figs. 2 to 5). For any wing different polar curves are obtained, depending upon the method of holding. Both C_L and C_D are affected. The results are shown in the figures, in which it is seen that the differences between the various tests are great, and that other discrepancies due to the tunnel itself as explained in the previous portion of this report, such as turbulence of the air stream and the limits of the cross section are negligible when compared to these. Three wing models and two complete airplane models tested first in the Eiffel and then in the Saint-Cyr tunnels gave results which were decidedly different when the supporting brackets were fastened above the model in one case and below in the other case. However, when the brackets were attached in the same manner the polar curves agreed within 2 or 3%, in spite of the fact that other conditions of test were different, such as differently placed honeycombs and a free stream in one case and a limited air stream in the other case. The interference of the supporting members seems to be very uncertain and it does not yet seem possible to form a law by which it might be calculated.

Results obtained on different wings with different methods of attachment do not even have a comparative value. Fig. 6 is given showing the curves of two wings held by the three different methods. The wing which is superior in aerodynamical qualities under one condition of test is inferior when held in another manner. When experimenting with a complete airplane model instead of an isolated wing the interference of the supports is much less noticeable. It seems as though the presence of the fuselage behind the wing had a stabilizing effect on the entire air flow about the wing.

It has been possible to show directly the effect of the support on the aerodynamic flow. These delicate experiments were carried out in the Eiffel laboratory by M. Lapresle. This work was done by holding the wing on a U-shaped frame (Fig. 7) and bringing the support very close to the surface of the wing and measuring its effect on the aerodynamic characteristics of the wing. The results show that the presence of the support near the upper side of the wing very perceptibly reduces the lift, 6% for one wing and 20% for another. On the contrary, the interference of a supporting spindle below the wing or behind it in the plane of the wing does not appreciably affect the drag. Supporting the wing by means of steel wires seems to be an excellent method.

Improvements to be Made in the Methods of Experiment in Wind Tunnels.

In order to determine a law of rigorous mechanical similitude and to apply this law to results obtained in model tests, it would therefore be necessary to either eliminate or correct by calculations the different errors herein agreed with, so that the results would be the same as those which would be realized if the model and the air flow were exactly similar to the full-scale condition. Let us see what measures would be necessary in order to more readily realize these conditions.

I. Geometrical Similitude.- For parts of the airplane (wing, fuselage, etc.), geometrical similitude may be easily attained. For a complete model, however, this can not be done, and we have already spoken of the errors which may be caused by not including to scale such details as the radiator hood, etc., and we also see that similarity can not even be approached for certain parts, such as streamlined stay wires and struts. It is therefore necessary to adopt the following method. That is, to build the model, eliminating the above-mentioned parts and to study separately in the wind tunnel the resistance of these eliminated parts either in full size as with stays and struts, or at least in size nearly full scale, and then correcting the coefficients obtained on the model for the parts which had been omitted.

II. The Relative Motion of the Airplane and the Fluid and the Effect of the Limited Air Stream.- We may assume that no error is introduced by the use of a moving air stream at a stationary model. There is an error there due to the fact that the model is tested in a limited air stream and it is necessary to apply a correction to the velocity comparing it with that which it would be for an infinite air stream, where the velocity V would be at an infinite distance from the model. Theory formulas give this correction. They do not seem to be exact and it may be possible to modify them to give a correction which may be applied in practice. It is undoubtedly difficult to measure the degree of turbulence in the air stream and it will probably be necessary to use the following limitation; that is, to bring the air to such a state of turbulence as may be defined by the coefficient of resistance for a sphere under standardized conditions.

III. Interference of Supporting Members.- A standard method of supporting models should be arrived at and this should be one which will have the least effect upon the results. It would be necessary to carry out a careful research on this problem. It would seem that the best support might be obtained by very thin and stiff brackets fastened below the wing or else by steel wires.

The Application of a Law of Similitude.

By observing the rules for testing above given and applying to the results certain corrections for errors which can not otherwise be eliminated, wind tunnel tests may be brought to an accuracy of the order of 2 to 5% when testing under standard conditions. It now remains to be seen whether a law of similitude from which the aerodynamic coefficients for large bodies may be obtained from the model tests. In order to have mechanical similarity, it is necessary that the motion of the fluid about the model and the full-sized body be similar. For non-viscous and non-compressible fluids it may be theoretically shown that this will be the case if the two bodies are geometrically similar. This has been confirmed even for fluids having a certain viscosity such as water, and in testing model hulls it may be assumed that the wave motion on the surface of the water about the ship will be similar to that about the model. Calculations based on this fact have been verified in practice. But for fluids such as air whose kinematic viscosity is thirteen times greater than that for water, this is no longer true. Many experiments have clearly shown that for similar bodies the types of air flow are often entirely different. It therefore becomes necessary to introduce the effect of the viscosity of the fluid. An effect which may be represented by a single parameter is the kinematic viscosity ν. In applying the general equations of hydrodynamics it may be shown that the motion of a fluid about two geometrically similar bodies will be similar if the coefficient VD/v is the same for both cases. This coefficient is known as Reynolds number and is called E. V is the velocity of the fluid at an infinite distance from the immersed body, and D a dimension of the body (for wings taken as the chord). If the fluid is also compressible it is no longer possible to find conditions for which the fluid motion will be similar. This may be neglected however because a theoretical analysis shows that for the present range of airplanes we can assume that the error introduced by the compressibility of the air is negligible. It should be noted however that this does not hold for propeller tips where the relative velocities between the air and the blade reach values as high as 300 to 250 m/sec. Therefore, excepting for the case of the propeller there will be about the reduced size model air flow mechanically similar to that which prevails about the full-size body if in both cases VD/v is the same. If this is true, the pressure at two homologous points over the fluid will be proportional to ρV^2. The influence of Reynolds number on the air flow may be seen from the appearance of the curve of $R/\rho V^2 D^2$ (the unitary coefficient) as ordinates and VD/v as abscissa. An examination of the appearance of these curves is of great practical interest. Actually the construction of wind tunnels does not permit us to reach the full scale VD. This number is only about one-twentieth as great for the model as for the full scale. If, therefore, between the range of the model and of the full scale the curve is inclined to the horizontal axis it is not possible to apply to the full scale the coefficient which was found from the model test. If, on the contrary, the curve is practically parallel to the VD axis, this may be done.

For thin wings the critical values of VD may be easily exceeded and apparently a region is reached where the resistance coefficient is practically constant. For thick wings the air flow is more unstable and M. Eiffel announced in 1914 that between the velocities of four and thirty m/sec, three distinct types of air flow existed. In practice if we exceed velocity of 20 m/sec, the coefficient is nearly constant for low lifts but varies at high angles of attack. While assuming that the VD curve remains practically constant throughout the entire unexplored region and that it is possible to apply to the full-size airplane the coefficients obtained from the model, it would be of the greatest interest to experiment in this region. This can be done either by full flight tests of the aircraft or on large models placed on a testing car or else by modifying the wind tunnels. Experiments on airplanes in flight would be the most complete and most instructive. These should be done first in gliding flight in order to eliminate the errors necessarily introduced by the variation of engine torque and propeller efficiency with altitude.

Unfortunately, full flight tests involve numerous difficulties. The measurement of angles and velocities has not yet been made with the desired precision and the experimental methods, and the existing instruments must be improved. The use of an aerodynamic testing car permits of more accurate measurement. Such an installation exists at the aerodynamic institute at Saint-Cyr. It was not used during the war but experiments are now being undertaken with it. It is to be hoped that these experiments in conjunction with those in gliding flight which are also being made at the present time, will provide valuable information on this important subject, and will give us points on the resistance curve for high values of VD. We will then know with what precision the results of wind tunnel tests may be applied. It should be noted that recent improvements in wind tunnels will reduce the range which now exists between the known values of VD and that tunnels will soon be operating with velocities of 80 m/sec, in which models 1.20 m to 2 m span or sections of full-size wings may be tested. In addition to these wing sections, a number of other component parts of the airplane may be tested in full size but slightly reduced.

A minute and detailed study in the tunnel of the resistance of individual parts, such as the section drag and induced drag of wings and the interferences, provides a method which might possibly be preferable to that of testing a complete model. In this manner a polar curve of a complete airplane could be drawn up from the individual curves measured from the detached parts such as wings, fuselage, landing gear, etc., by adding the resistances of the individual parts and correcting for interference. This method applied with great care and skill by M. Toussaint to a biplane model enabled him to reconstruct the curve of the complete model from those of the individual component parts.

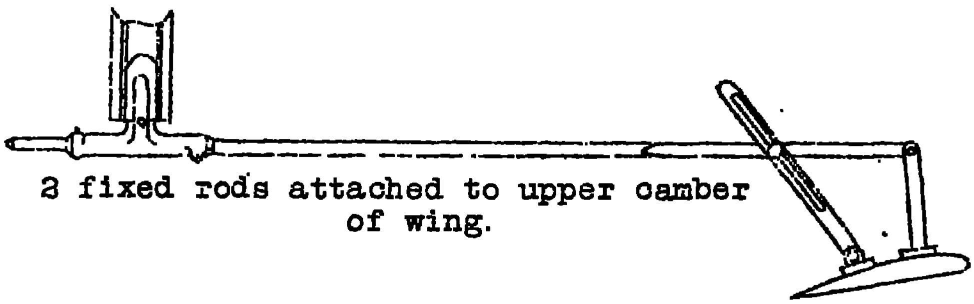
Conclusion.

Aerodynamic research in the wind tunnel has already been of inestimable value. It has permitted the formulating of a number of important laws relating to the resistance of air and has revealed the particular phenomena resulting from the action of air against lifting surfaces. It has in addition been of the greatest aid to builders. In spite of the great work which has been done it now becomes necessary to require from laboratories a greater precision of testing.

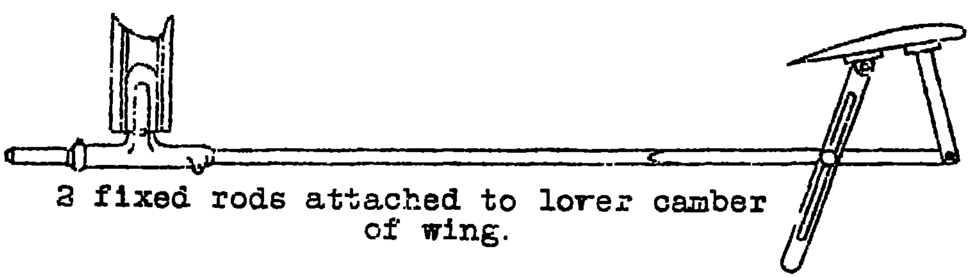
The purpose of this article has been to show how this greater accuracy might be attained. The first step will be to improve the conditions of experiment by adopting a uniform and accurate method which will give corrected results which relate to standard conditions and which may reasonably be used to calculate the true aerodynamic coefficients of a flying airplane. The adoption of a standard method of testing should be accompanied by the adoption of a uniform notation in all laboratories that have dimensional coefficients being preferable. In the second place, it would be of great interest to execute tests on airplanes in flight or on full-sized bodies on the test car so that we might know in at least a few cases the resistance coefficients for high values of VD. If we had careful, accurate and uniform tests in the wind tunnel on one hand, and full scale tests from full flight on the other hand, it would be possible to formulate a law of similitude and by its application to increase the value of wind tunnel tests.

Translated by D. L. Bacon, NationalAdvisory Committee for Aeronautics.

Influence of supports on results obtained in experiments.



2 fixed rods attached to upper camber of wing.



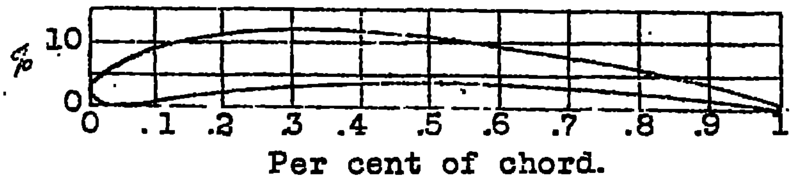
2 fixed rods attached to lower camber of wing.

1 spatula attached to lower camber at trailing edge.

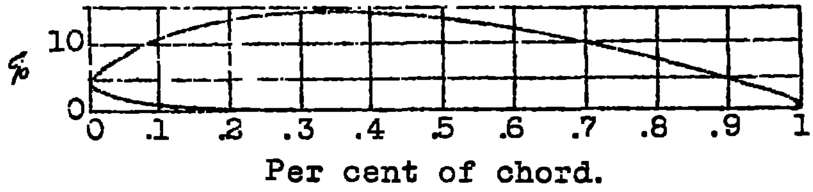
Fig. 1 (Continued on page 16)

Aerofoils used in tests.

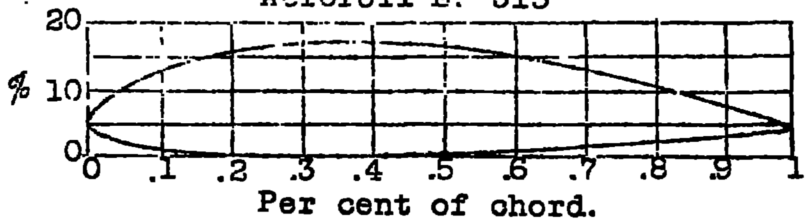
Aerofoil E. 308 B



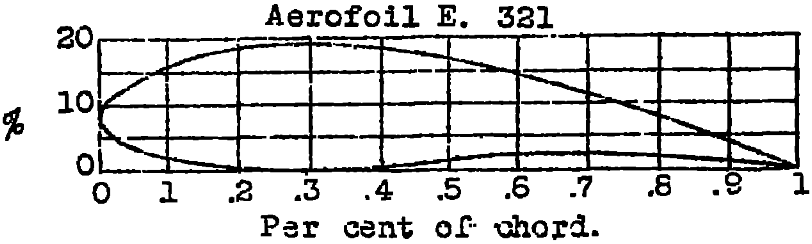
Aerofoil E. 312



Aerofoil E. 315



Aerofoil E. 321

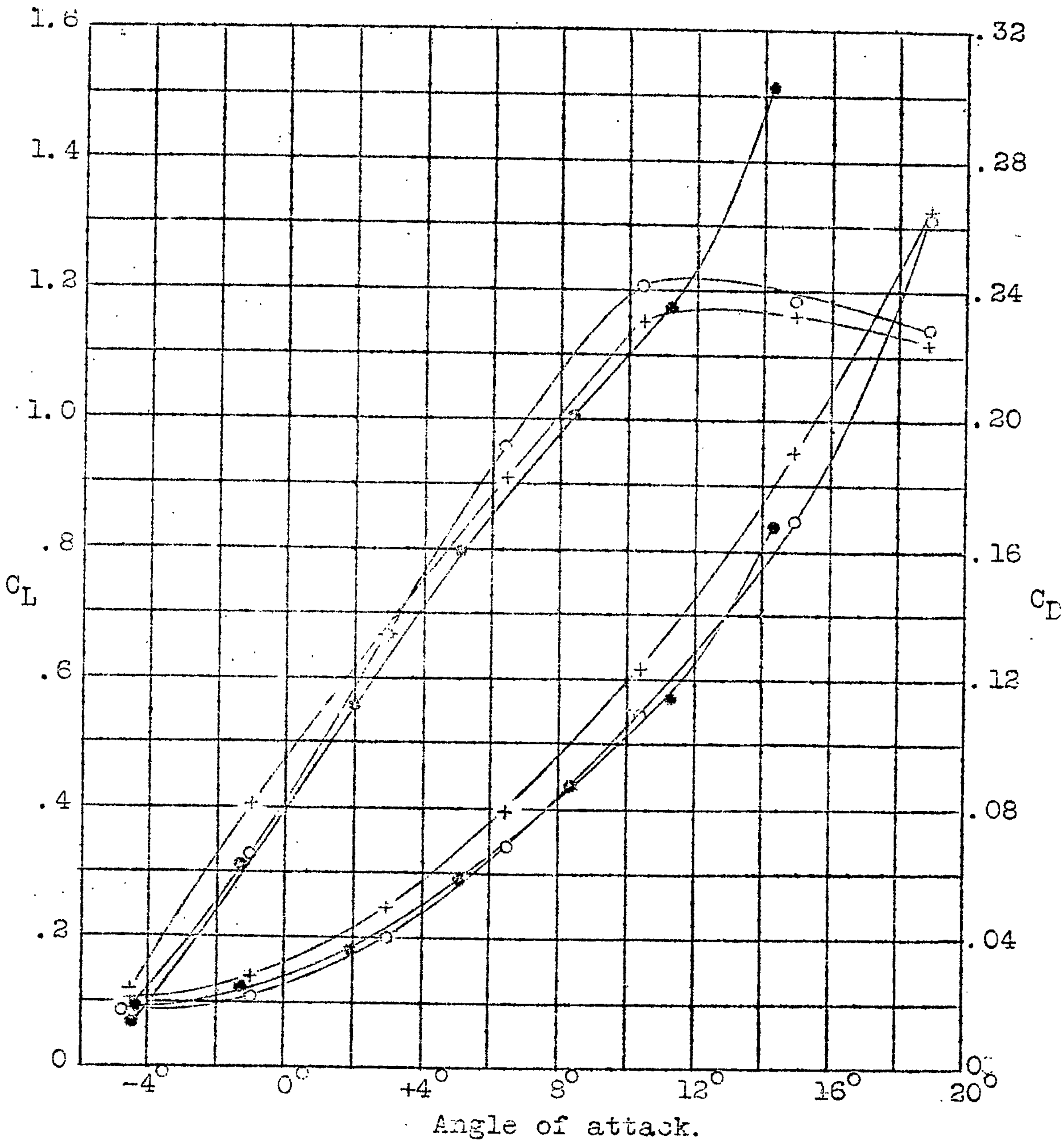


(Fig. 1 continued).

+ attachments on upper camber.

○ " " lower "

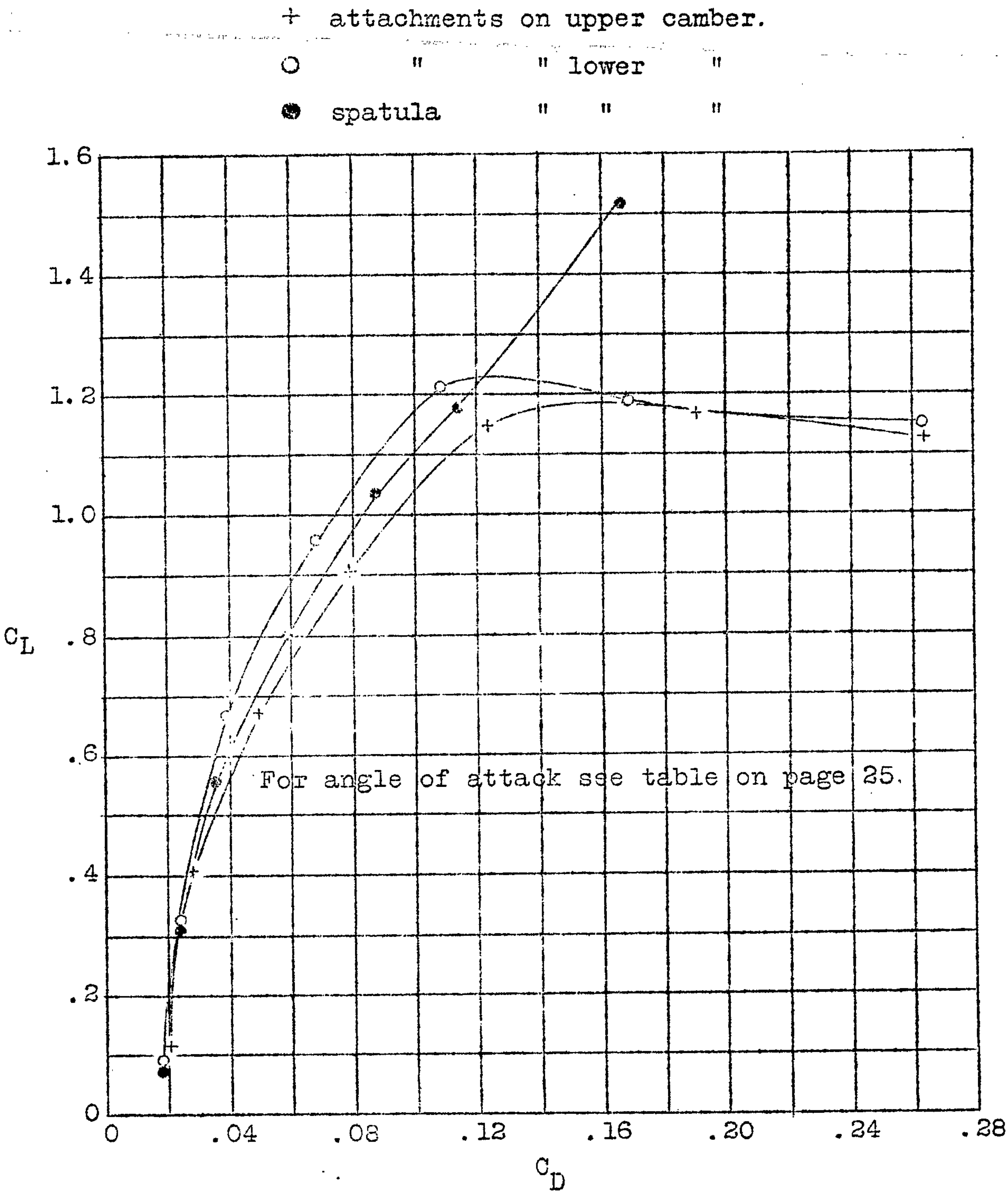
● spatula " " "



Aerofoil E 308 B on page 16.

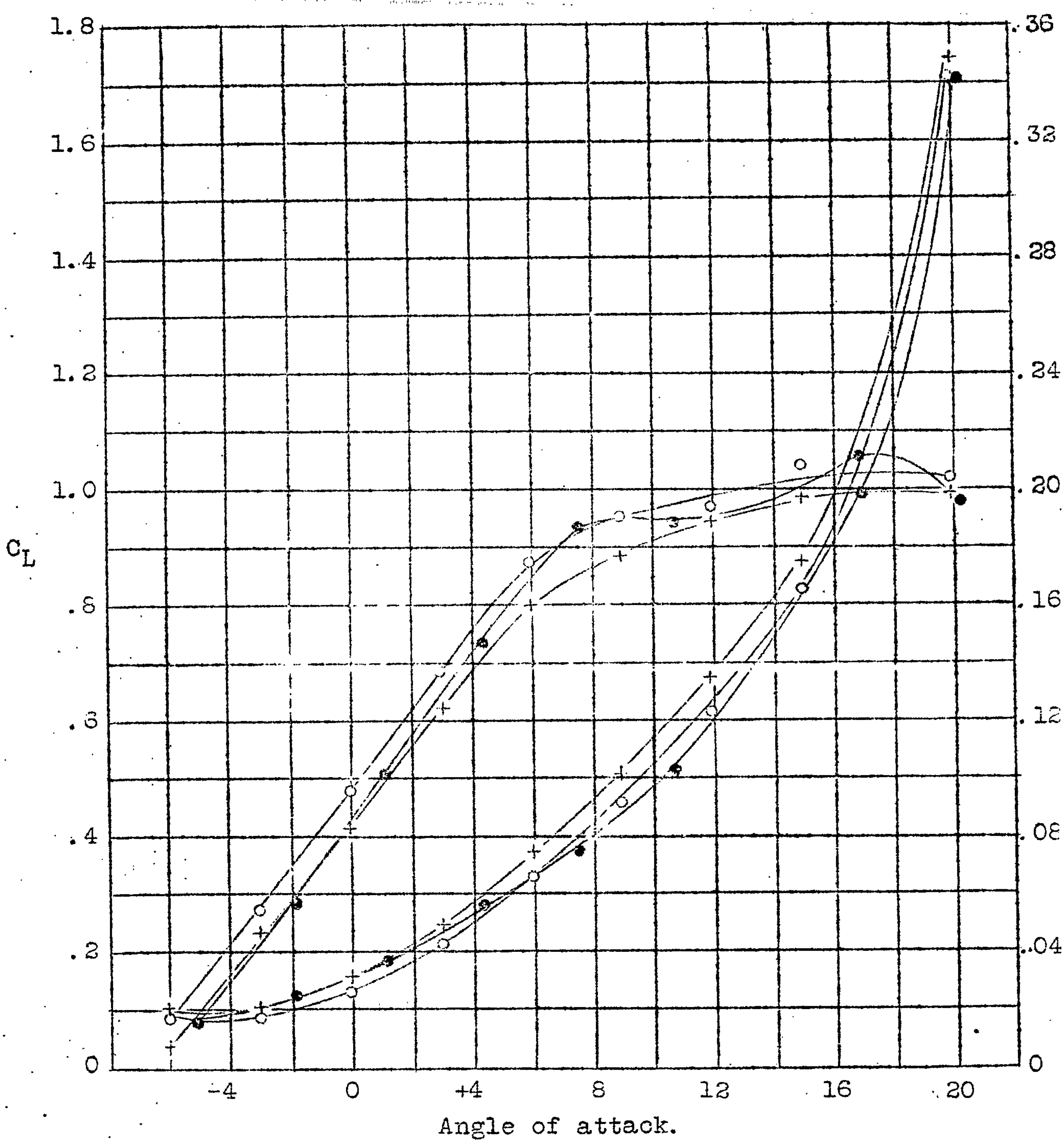
Table of characteristics on page 25.

Fig. 2 (Continued on page 18).

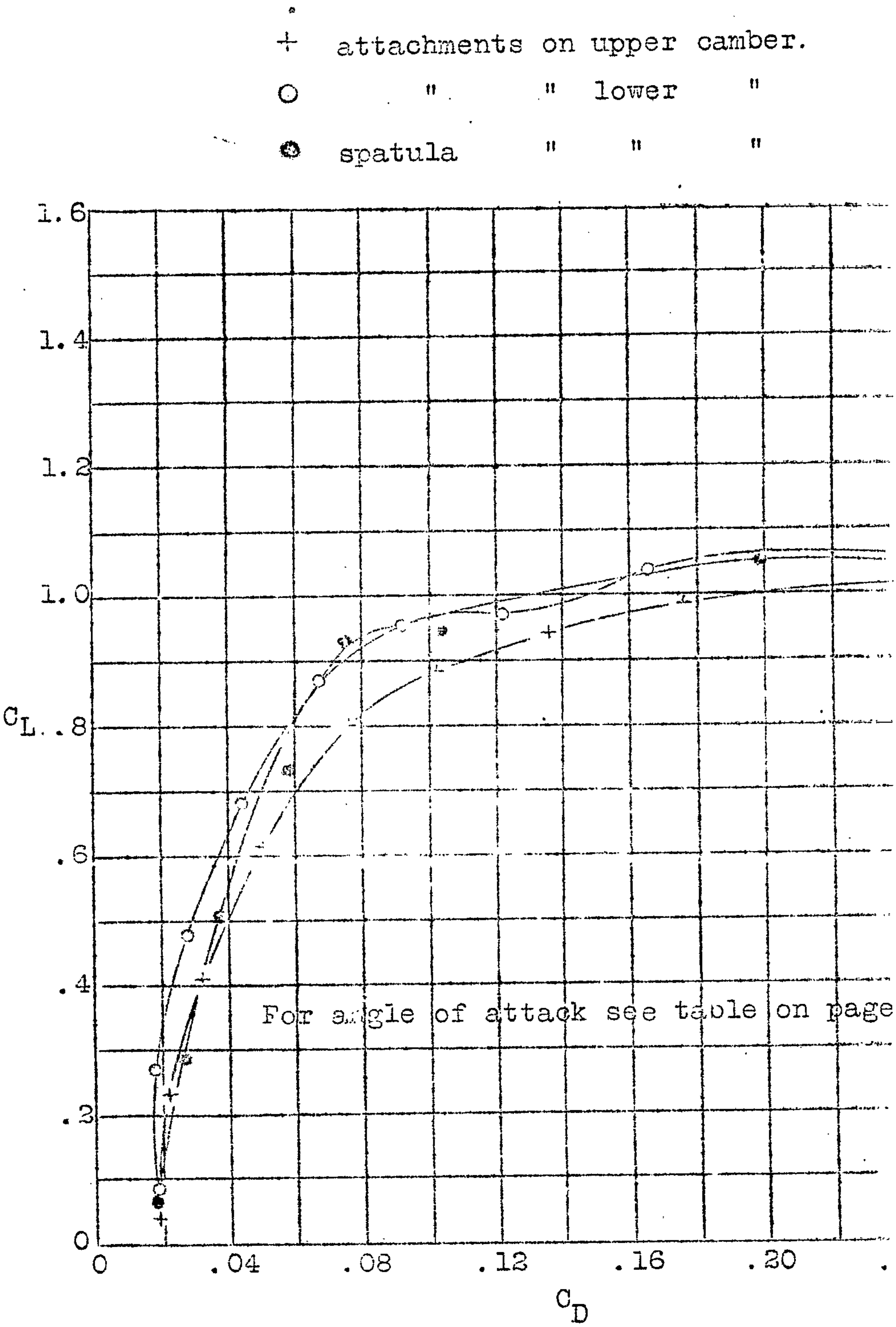


Aerofoil E 308 B on page 16.
Tables of characteristics on page 25.
Fig. 2 (Continued from page 17).

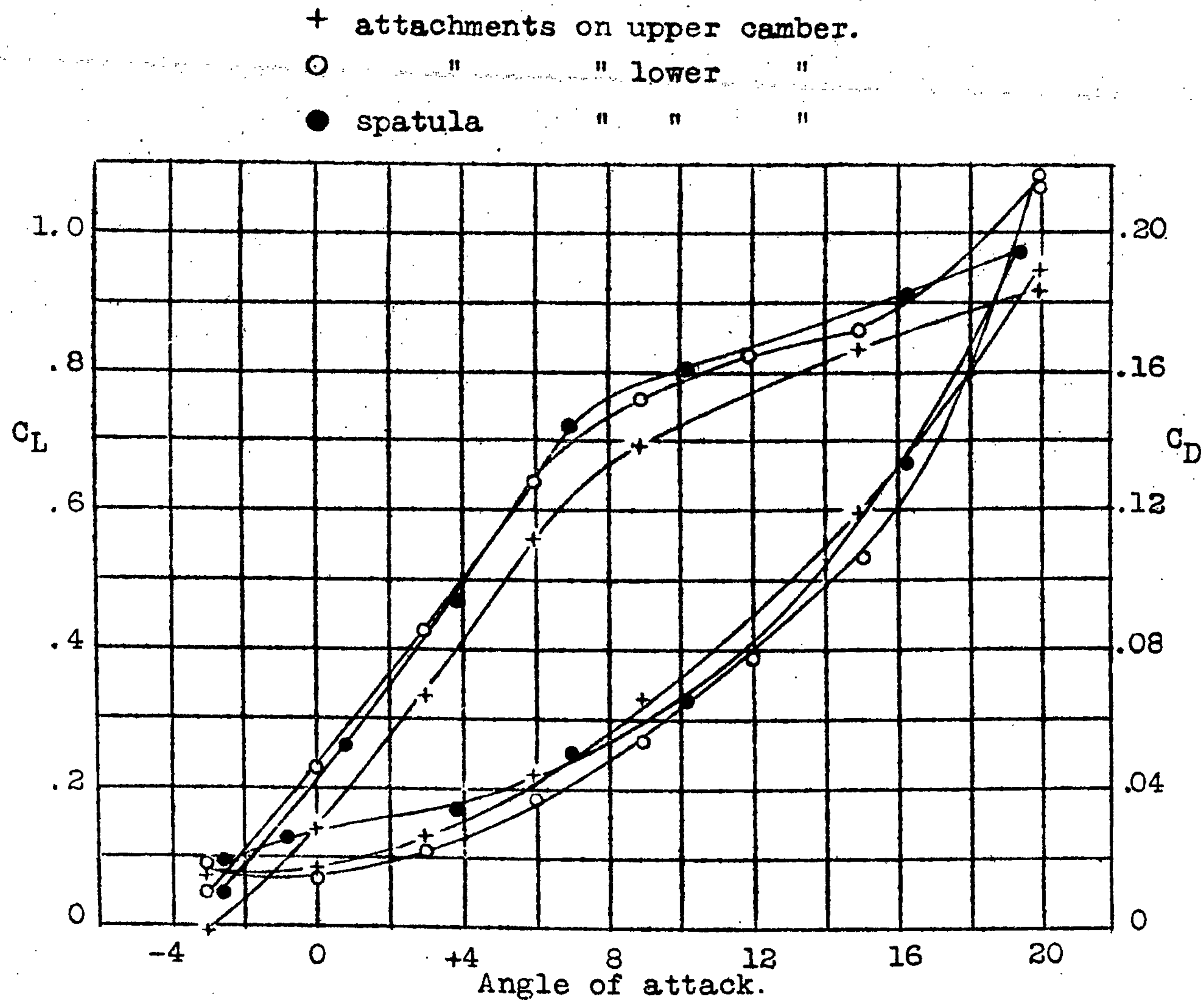
+ attachments on upper camber.
O " " lower "
● spatula " " "
Study on importance of interactions.



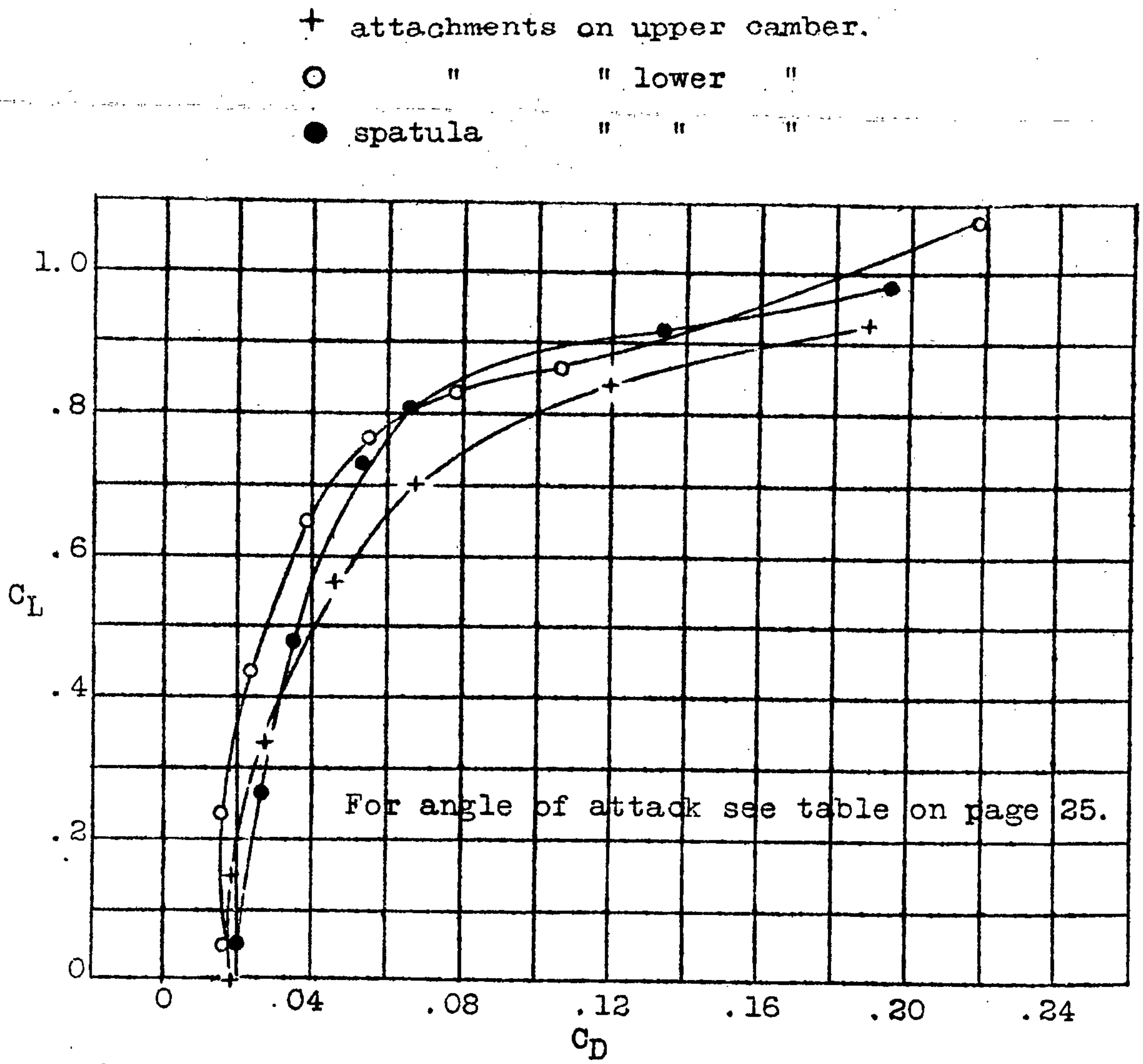
Aerofoil E 312 on page 16.
Table of characteristics on page 25.
Fig. 3 (Continued on page 20).



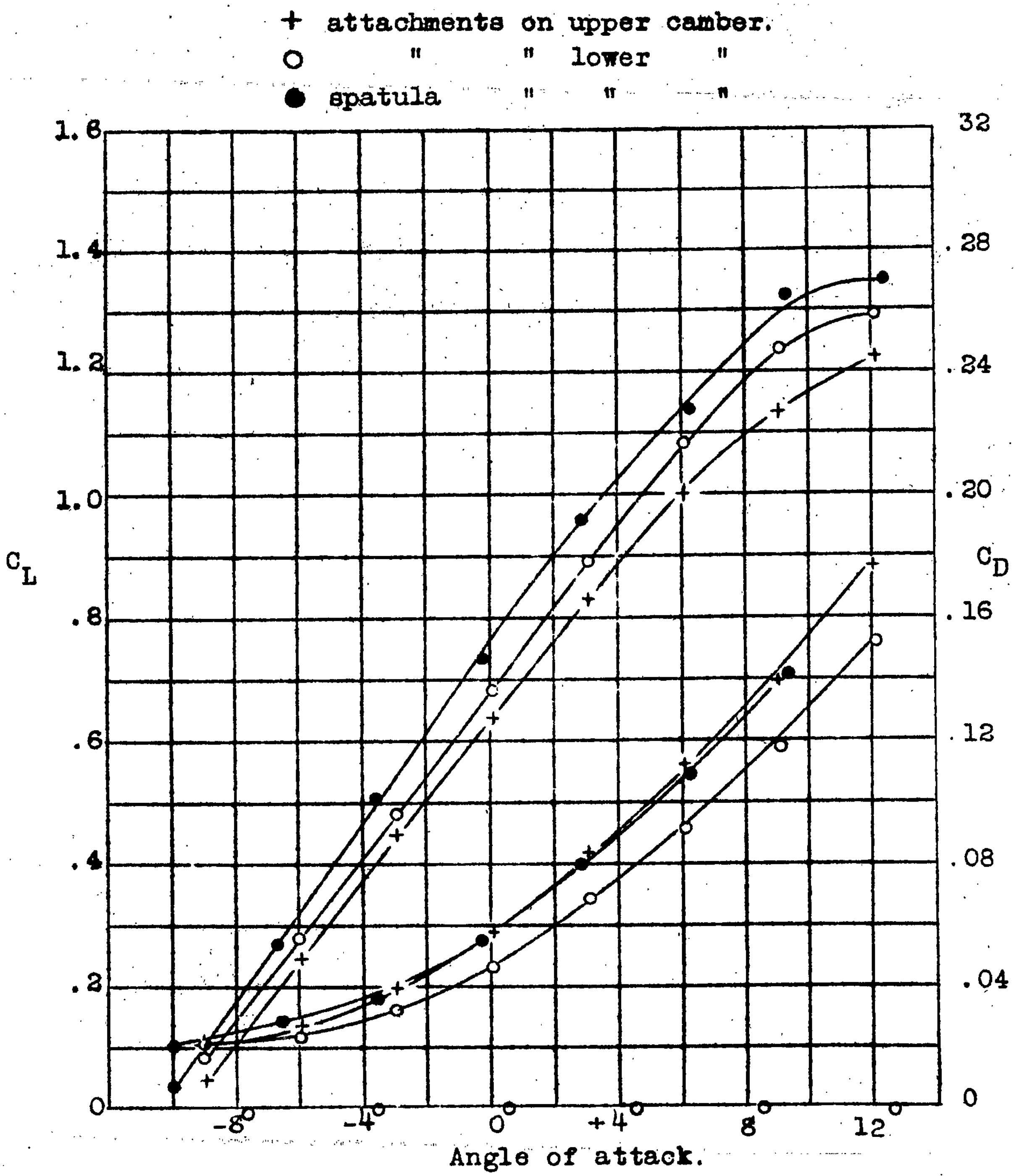
Aerofoil E 312 on page 16.
Tables of characteristics on page 25.
Fig. 3 (Continued from page 19).



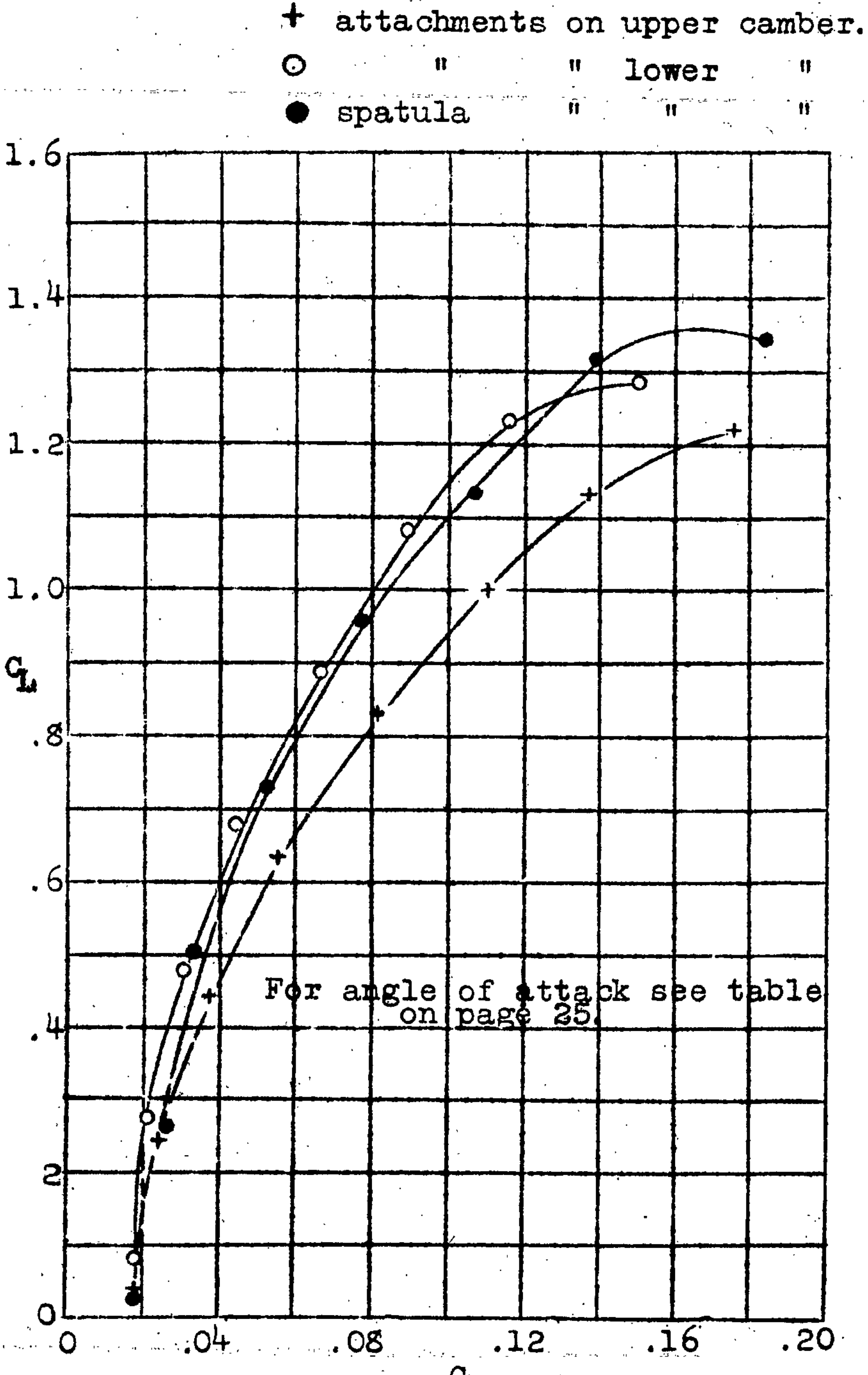
Aerofoil E 315 on page 16.
Table of characteristics on page 25.
Fig. 4 (Continued on page 22).



Aerofoil E 315 on page 16.
Tables of characteristics on page 25.
Fig. 4 (Continued from page 21).



Aerofoil E 321 on page 16.
Table of characteristics on page 25.
Fig. 5 (Continued on page 24).



Aerofoil E 321 on page 16.
Tables of characteristics on page 25.
Fig.5 (Continued from page 23).

Table of Characteristics.

Aerofoil E 308 B.

	○		+			●	
α	C_L	C_D	C_L	C_D	α	C_L	C_D
-4.5°	.0896	.01824	.11552	.02064	-4.4°	.0723	.01792
-1°	.3248	.02192	.4032	.02752	-1.2°	.3104	.02432
+3°	.6688	.03936	.6688	.04976	2°	.5568	.03568
6.5°	.9536	.0680	.9072	.07856	5.2°	.7984	.05904
10.5°	1.2080	.10800	1.1536	.12352	8.5°	1.0336	.08672
15°	1.1840	.16800	1.1680	.1904	11.4°	1.1744	.11408
19°	1.1424	.12624	1.1280	.2640	14.4°	1.5168	.1664

Aerofoil E 312

	○		+			●	
α	C_L	C_D	C_L	C_D	α	C_L	C_D
-6°	.08688	.01824	.0384	.01856	-5.1°	.0848	.01744
-3°	.272	.01792	.2368	.02160	-1.8°	.2880	.02576
0°	.480	.02736	.4128	.03168	+1.2°	.5104	.03648
+3°	.688	.04352	.6192	.04960	4.4°	.7360	.05664
6°	.8736	.06672	.8016	.07472	7.6°	.9344	.07536
9°	.9536	.09136	.8880	.10128	10.8°	.9456	.10368
12°	.9712	.12144	.9440	.13440	17°	1.0560	.1984
15°	1.040	.1648	.9904	.17520	20.2°	.9840	.3424
20°	1.0208	.3424	.9920	.3488			

Aerofoil E 315

	○		+			●	
α	C_L	C_D	C_L	C_D	α	C_L	C_D
-3°	.04976	.0176	-.00928	.01792	-2.6°	.05504	.01968
0°	.2336	.01568	.1440	.01680	+ .8°	.2640	.02608
+3°	.4320	.02272	.3360	.02688	3.8°	.4768	.03536
6°	.6480	.03808	.5600	.04576	7°	.7264	.05152
9°	.7632	.0544	.6992	.06624	10.2°	.8064	.06608
12°	.8240	.0784	--	---	16.3°	.9168	.13424
15°	.8624	.10640	.8384	.11920	19.5°	.9776	.1952
20°	1.072	.21840	.9232	.18960			

Aerofoil E 321

	○		+			●	
α	C_L	C_D	C_L	C_D	α	C_L	C_D
-9°	.08288	.01984	.04064	.01904	-10°	.03024	.01952
-6°	.2752	.02208	.2448	.02480	- 6.6°	.2640	.02656
-3°	.4768	.03104	.4448	.03824	- 3.6°	.5008	.03408
0°	.6784	.04464	.6368	.05616	+ .3°	.7296	.05312
+3°	.8896	.06688	.8304	.08224	2.8°	.9552	.07808
6°	1.0800	.09056	1.0080	.11104	6.2°	1.1328	.10816
9°	1.2320	.11712	1.1360	.13872	9.2°	1.3184	.14016
12°	1.2896	.15120	1.2208	.1760	12.3°	1.3440	.1824

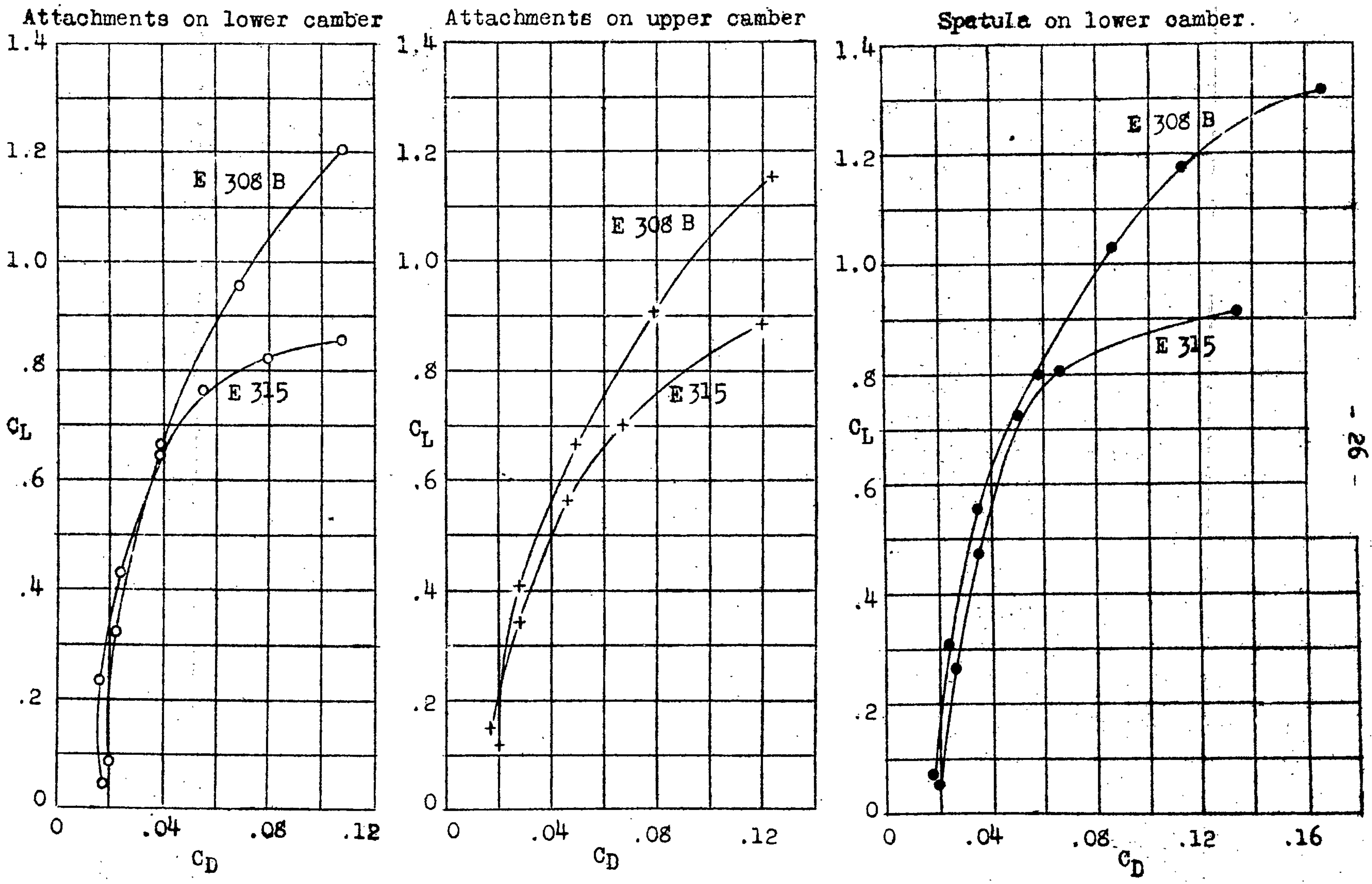
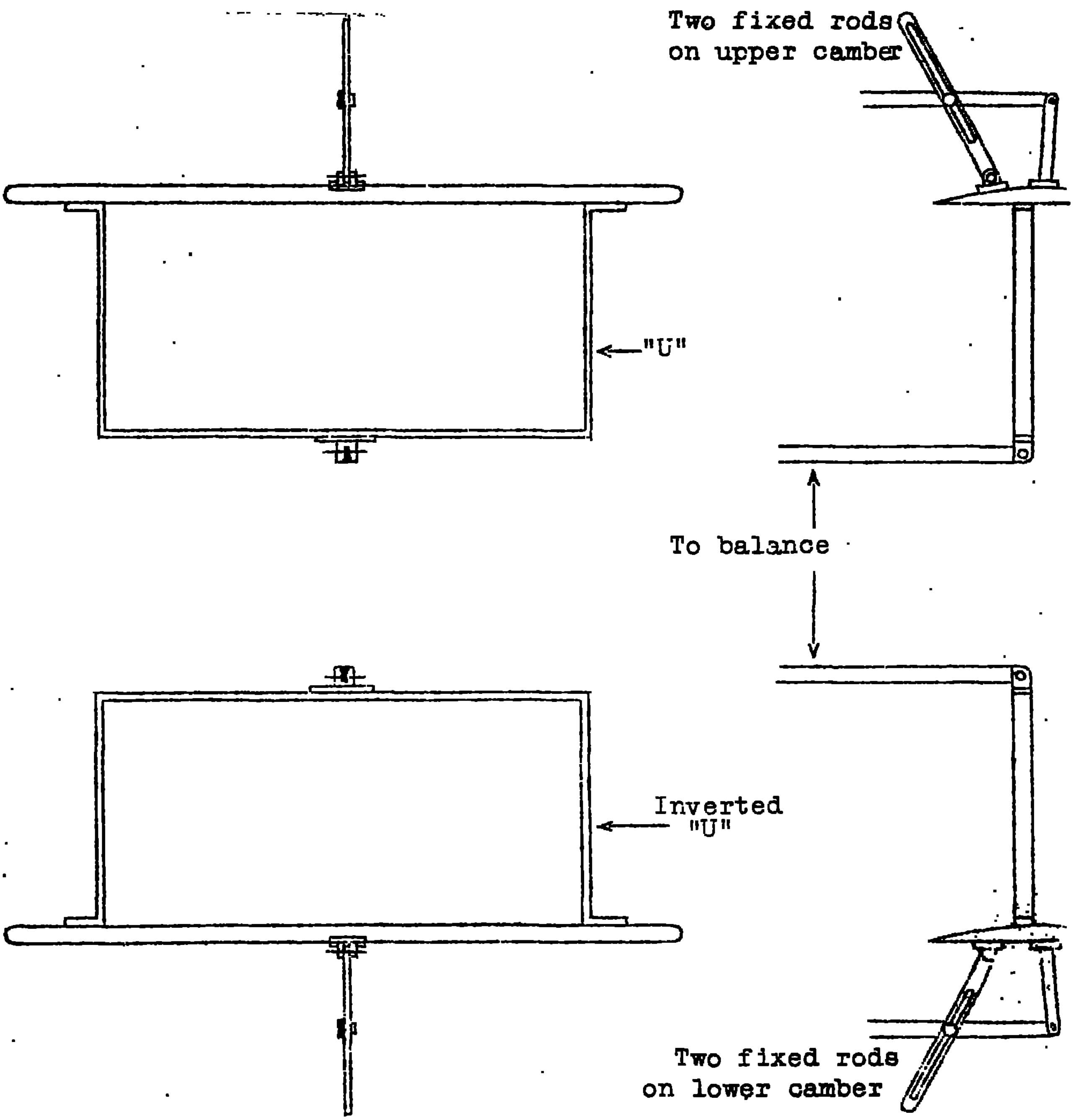


Fig. 6. Aerofoils E 308 B and E 315 on page 16. Tables of characteristics on page 25.



Comparison of effect of attachments.
Table of characteristics on page 28.

Fig. 7.

			Kind of Attachment.			
			None	Spatula	2 fixed rods on lower camber.	2 fixed rods on upper camber.
"U" on upper camber	E 308 B at 5.4°	Rx	97.5	96.0	96.0	
		Ry	710.7	704.3	703.2	
	E 315 at 1.5°	Rx	45.6	42.5	45.8	
		Ry	136.4	132.3	137.8	
"U" on lower camber.	E 308 B at 5.5°	Rx	72.3			76.6
		Ry	720.9			682.3
	E 315 at 1.8°	Rx	43.2			43.1
		Ry	251.1			207.0